

Interactions Between Micro- and Nano plastics and Engineered Nanoparticles in Wastewater and Receiving Environments: Implications for Treatment Performance, Transport Pathways, and Ecotoxicity

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Abstract

Microplastics (MPs), nanoplastics (NPs), and engineered nanoparticles (ENPs) are increasingly recognized as interconnected contaminants in wastewater treatment systems and receiving environments. This review examines their occurrence, interactions, treatment performance, transport pathways, persistence, and ecotoxicological implications, with emphasis on evidence from primary studies. The review considered research addressing wastewater, sludge, effluent, receiving waters, particle interactions, aggregation, treatment processes, and biological effects, with attention to analytical approaches capable of improving particle identification and characterization. Evidence from wastewater treatment plants shows that treatment systems can remove substantial proportions of MPs and related particles, but removal commonly represents redistribution rather than destruction. Sludge functions as a major retention compartment, while fine particles and fragmented materials can remain in treated effluent and reach receiving waters. Particle behaviour is strongly influenced by ionic strength, pH, salinity, dissolved organic matter, temperature, surface functional groups, particle aging, and interactions with mineral phases. These factors regulate heteroaggregation, colloidal stability, deposition, and transport across freshwater, brackish, and marine environments. Treatment related interactions can also alter sludge properties, microbial communities, extracellular polymeric substances, and

membrane operation without necessarily causing immediate deterioration in effluent quality. After discharge, particle mixtures may form transport hotspots in rivers and sediments and can influence microbial processes, antibiotic resistance patterns, oxidative stress, developmental responses, and food web functioning. Evidence from aquatic organisms further indicates that nanoscale particles and mixed exposures may produce stronger or distinct biological effects because of their high surface area, mobility, and carrier potential for engineered nanoparticles and associated contaminants. Overall, the literature indicates that wastewater treatment should be understood as a particle transformation and redistribution system rather than a complete removal barrier. Future research should prioritize realistic mixed particle exposures, size resolved assessments, wastewater relevant chemistries, improved analytical methods, and integrated evaluation of water and sludge pathways to strengthen environmental risk assessment and treatment strategies.

Keywords: *Microplastics; Nanoplastics; Engineered nanoparticles; Wastewater treatment; Heteroaggregation; Environmental transport; Ecotoxicity*

Section 1. Introduction

Microplastics and nanoplastics have moved from being treated as a peripheral pollution issue to becoming a central concern in wastewater science because wastewater treatment plants now function as major collection points for plastic particles from households, industry, and urban runoff. Recent primary studies show that conventional treatment can remove a large share of these particles, yet removal is incomplete, fragmentation can continue within the treatment train, and a substantial fraction is diverted to sludge rather than eliminated from the system (Monira *et al.*, 2023). At the same time, full scale wastewater evidence shows that metal-based nanoparticles are also present across influent, post primary treatment, effluent, reclaimed water, and sludge, with concentrations and particle sizes changing across each stage of treatment (Cervantes-Avilés & Keller, 2021). This matter because the treatment plant is not simply a barrier; it is also a reactive environment where plastics, nanoparticles, salts, organic matter, and microbial biomass interact in ways that can alter fate, transport, and eventual release (Choi *et al.*, 2023). The growing overlap between micro and nanoplastics and engineered nanoparticles therefore deserves attention as a coupled exposure problem rather than as separate pollution stories (Cervantes-Avilés & Keller, 2021; Choi *et al.*, 2023; Monira *et al.*, 2023).

A key reason for this shift is that nanoplastics are not just smaller versions of microplastics. Recent primary evidence shows that their aggregation behavior depends strongly on particle weathering and natural organic matter, with pristine nanoplastics and photochemically weathered nanoplastics responding differently in electrolyte solutions because organic coatings can either stabilize or destabilize them (Xu *et al.*, 2025). That distinction is important for wastewater because it helps explain why nanoplastics may follow transport routes that are not identical to those of larger particles, especially when dissolved organic matter, salts, and sludge solids are present. Direct analytical work in environmental and potable waters has also confirmed that nanoplastics occur as measurable polymer specific particles across real water samples, with polyethylene, polyethylene terephthalate, polypropylene, and polystyrene among the dominant forms detected in low microgram per liter ranges (Okoffo & Thomas, 2024). In parallel, direct observation in global ocean water has shown that nanoplastics reach receiving waters in diverse shapes, including nanofibers, nanoflakes, and mixed morphologies, reinforcing the view that these particles are environmentally persistent and physically distinct from the larger fragments

from which they originate (Moon *et al.*, 2024). Taken together, these findings justify treating nanoplastics as a separate exposure class with its own fate, transport, and analytical challenges rather than assuming that they behave like ordinary microplastics (Moon *et al.*, 2024; Okoffo & Thomas, 2024; Xu *et al.*, 2025). The ecotoxicological relevance of this distinction is equally important. Wastewater based experiments have shown that different microplastic categories can reshape bacterial community structure and antimicrobial resistance gene abundance, while wastewater treatment does not necessarily reduce those genes effectively (Tran *et al.*, 2025). That finding is a useful warning for nanoplastics and engineered nanoparticles as well, because small particles with high surface area can act as reactive carriers, modify microbial attachment, and influence the mobility of associated contaminants within treatment systems and receiving waters. In practical terms, this means that the environmental risk of plastic particles should no longer be framed only as an issue of litter visibility or simple particle counts. It should also be framed around how particle size, surface chemistry, and co exposure with engineered nanoparticles affect removal efficiency, sludge partitioning, downstream transport, and biological response in aquatic recipients. A modern understanding of wastewater pollution must therefore integrate treatment performance with particle transformation and ecotoxicity, because the particles that escape treatment are the ones most likely to shape exposure in rivers, estuaries, and marine waters (Cervantes-Avilés & Keller, 2021; Choi *et al.*, 2023; Monira *et al.*, 2023; Moon *et al.*, 2024; Okoffo & Thomas, 2024; Tran *et al.*, 2025; Xu *et al.*, 2025).

2. Methods

2.1 Search strategy for the review

The search strategy was structured around three linked concepts: particle type, treatment setting, and environmental fate. The particle type block covered microplastics, nanoplastics, engineered nanoparticles, and coupled particle complexes. The treatment setting block included municipal and industrial wastewater treatment plants, primary and secondary sludge, membrane systems, activated sludge, aerobic granular sludge, and sludge fermentation units. The fate block included effluent discharge, surface water, sediment, and organism exposure. In practice, this meant that the search string was broad enough to capture studies that used different terminology for the same phenomenon, but strict enough to keep the synthesis focused on real environmental data rather than theoretical discussion. The review also favored studies that used robust identification tools such as nano flow cytometry, micro Raman spectroscopy, laser direct infrared spectroscopy, and depolymerization coupled chromatographic confirmation, because those methods reduce the risk of visual misclassification and improve confidence in size and polymer assignment (Iskandarani *et al.*, 2025; Miserli & Konstantinou, 2025; Ren *et al.*, 2025).

A two stage screening logic was applied. First, titles and abstracts were screened for direct relevance to wastewater, sludge, receiving waters, and particle interaction. Second, full texts were checked for actual primary data. Studies were only retained when they reported original sampling, experimental dosing, or quantitative removal or interaction results. This is important because wastewater microplastic research has become methodologically diverse, and a large body of published material now consists of reviews that discuss the field but do not contribute new measurements. To preserve the empirical character of the review, the selected studies were therefore anchored in observed particle burdens, observed heteroaggregation behavior, observed process response, and observed transport outcomes rather than secondary synthesis. That approach also created a cleaner bridge between the analytical methods used in the source studies and the mechanistic questions addressed in later subsections (Iskandarani *et al.*, 2025; Miserli &

Konstantinou, 2025; Ren *et al.*, 2025).

2.2 Primary Study Evidence on Occurrence, Abundance, Morphology, and Polymer or Nanoparticle Types in Wastewater and Sludge

Primary studies from different treatment contexts show a clear pattern: wastewater treatment plants are not only interception points but also particle sorting environments. In Bangkok, a comparison of centralized and decentralized domestic plants found microplastics in both wastewater and sludge, with removal efficiencies ranging from 50 to 96.8 percent in centralized plants and 14.2 to 53.6 percent in decentralized plants. The same study also showed that retained particles in sludge reached 20,000 to 228,100 particles per kilogram dry weight, confirming that sludge is a major accumulation compartment rather than a simple by product. In Ho Chi Minh City, industrial wastewater treatment plants showed microplastic concentrations of 0.3 to 40.4 items per liter in wastewater and 29.6 to 92.0 items per gram dry weight in sludge, with fibres dominating both streams and daily discharge still reaching 1.7 million particles despite high removal efficiency. In Chengdu, influent concentrations ranged from 177 to 517 particles per liter, overall removal reached 89.3 to 94.6 percent, and sludge again carried the heaviest burden, especially for polypropylene and polyethylene. Together, these primary studies show that the main profile across wastewater systems is not simply the presence of plastics, but their redistribution into different compartments, with sludge acting as a concentrated reservoir while effluent remains an important release route (Maw *et al.*, 2024; Kieu-Le *et al.*, 2025; Lv *et al.*, 2025). Particle size and morphology also change across treatment units. The Bangkok study reported that synthetic fibres and fragments were the dominant forms, reflecting inputs from clothing, domestic activities, road wear, and mixed municipal waste. In the Greek municipal plant studied by Miserli and Konstantinou, fragments were the most representative shape in both effluent wastewater and sludge, while fibres, spheres, and films were also observed. The same work found a broad polymer profile, led by polyamide, polyacrylic acid, and polyacrylamide co polyacrylic acid, followed by PVC, PBMA, PE, PS, PP, PVA, and PVB, which demonstrates that wastewater matrices can capture not only common consumer plastics but also specialty polymers and additives from personal care and industrial products. This matters because the polymer mix changes the density, surface energy, and likely fate of particles in sludge and receiving waters. It also reinforces the idea that occurrence studies should not be reduced to counts alone, because a low number concentration can still conceal a chemically diverse and physically mobile particle population (Maw *et al.*, 2024; Lv *et al.*, 2025). The same theme appears in the Chengdu study, where removal efficiency was strongly size dependent. Large particles above 1 millimeter were removed efficiently in primary treatment, but particles below 0.2 millimeter were much harder to retain, and the proportion of very small particles increased again in later treatment stages, suggesting fragmentation under hydraulic shear. This is a useful reminder that wastewater plants do not simply filter plastics out; they can also transform the particle size distribution in ways that shift the risk profile. The study also showed that the final effluent still carried small, dense particles such as PET fibres, which are more likely to persist in rivers and sediments after release. Combined with the Bangkok and Ho Chi Minh City evidence, the finding supports a practical conclusion: the current operational challenge is not only how to maximize removal, but how to prevent fragmentation, keep fine particles from escaping, and reduce sludge based re export to the environment (Kieu-Le *et al.*, 2025; Lv *et al.*, 2025).

Table 1 summarizes primary study findings on the occurrence, abundance, morphology, and dominant polymer or nanoparticle types reported in wastewater and sludge. It validates Section

2.2, by highlighting differences in particle characteristics and distribution across treatment systems.

Table 1. Primary study evidence on occurrence, abundance, morphology, and polymer or nanoparticle types in wastewater and sludge

System and matrix	Main findings	Particle profile	Citation(s)
Centralized and decentralized domestic WWTPs in Bangkok	Sludge was the main retention pool; removal varied widely by plant type	Fibres and fragments dominated	(Maw <i>et al.</i> , 2024)
Municipal WWTPs in Chengdu	High removal for large particles, lower retention for fine particles, fragmentation in later stages	PP and PE dominated sludge; PET fibres remained in effluent	(Lv <i>et al.</i> , 2025)
Industrial WWTPs in Ho Chi Minh City	High removal did not eliminate daily environmental release	Fibres dominated wastewater and sludge; daily discharge persisted	(Kieu-Le <i>et al.</i> , 2025)

Main occurrence patterns reported in primary studies, including abundance, morphology, and dominant particle types in wastewater and sludge. MPs, microplastics; NPs, nanoparticles; WWTPs, wastewater treatment plants; PP, polypropylene; PE, polyethylene; PET, polyethylene terephthalate; PVC, polyvinyl chloride; PBMA, poly butyl methacrylate; PVA, polyvinyl alcohol; PVB, polyvinyl butyral.

2.3 Mechanistic Evidence on Heteroaggregation, Deposition, and Transformation Under Different Solution Chemistries

The mechanistic literature shows that particle interaction is governed less by a single universal rule and more by a balance among surface charge, solution chemistry, particle age, and mineral context. In a foundational study on fragmental PET nanoplastics, aggregation kinetics changed markedly with electrolyte composition, pH, and humic acid. Electrolytes reduced electrostatic repulsion and accelerated aggregation, while humic acid altered colloidal stability in a concentration and chemistry dependent way. That work is important because it demonstrates that even when particles begin as small, mobile fragments, their fate can quickly shift toward cluster formation once they enter realistic aqueous matrices. A second primary study on sulfate modified polystyrene nanoplastics reached a related conclusion in synthetic and natural waters: stability was not fixed, but varied with water chemistry and the degree of surface modification. Together, these studies show that nanoplastics are highly responsive colloids rather than inert fragments, and that wastewater chemistry can either stabilize or destabilize them depending on the exact ionic and organic background (Dong *et al.*, 2021; Wang *et al.*, 2021).

Heteroaggregation with mineral surfaces adds another layer of complexity. When polystyrene nanoplastics were exposed to alumina, the particles showed significant heteroaggregation and deposition, especially under acidic and neutral conditions. Higher ionic strength promoted removal from suspension, while increasing pH suppressed aggregation. A similar pattern was later confirmed with goethite, where polystyrene nanoplastics heteroaggregated with FeOOH and the process was accelerated when the particles carried surface functional groups such as amino or

carboxyl moieties. Again, higher salt concentrations promoted removal, whereas higher pH weakened the interaction. These results matter for wastewater and downstream waters because alumina and iron oxyhydroxides are common mineral phases in natural particles, treatment residuals, and suspended solids. In other words, nanoplastics do not move through water alone; they interact with the mineral background and become part of larger heteroaggregates that have different settling and transport properties than the original particles (Wu *et al.*, 2022).

The combined interpretation of these studies is that wastewater chemistry acts like an invisible traffic controller. Low pH and high ionic strength compress the electrostatic double layer and make collisions more likely to result in stable attachment. Natural organic matter can behave in a more nuanced way, sometimes stabilizing particles by steric effects and sometimes promoting bridging or bridging like attachment depending on how it adsorbs to the particle surface. Surface functionalization is equally important, because amino, carboxyl, and sulfate groups change how the nanoplastic interacts with cations and mineral surfaces. For wastewater systems, this means that the same particle may behave differently in influent, activated sludge liquor, membrane feed, and receiving water. That is why the mechanistic literature is so useful: it explains not only whether particles aggregate, but why the same particle may remain suspended in one compartment and deposit in another (Dong *et al.*, 2021; Wang *et al.*, 2021; Wu *et al.*, 2022).

Table 2 presents evidence on how solution chemistry influences the aggregation, deposition, stability, and transformation of nanoplastics and their interactions with mineral surfaces. It substantiates Section 2.3, by comparing the main chemical factors controlling particle behaviour.

Table 2. Mechanistic evidence on heteroaggregation, deposition, and transformation under different solution chemistries

Interaction system	Chemistry controlling behavior	Main mechanistic insight	Citation(s)
PET nanoplastics in aqueous solution	Electrolytes, pH, humic acid	Aggregation kinetics shifted strongly with water chemistry	(Dong <i>et al.</i> , 2021)
Sulfate modified PS nanoplastics in synthetic and natural waters	Synthetic and natural water composition	Stability varied with salinity and organic background	(Wang <i>et al.</i> , 2021)
PS nanoplastics on alumina and goethite	pH, ionic strength, surface functional groups	Heteroaggregation and deposition were enhanced by salts and lower pH	(Wu <i>et al.</i> , 2022)

PET, polyethylene terephthalate; PS, polystyrene; Al₂O₃, alumina; FeOOH, iron oxyhydroxide; pH, potential of hydrogen; humic acid refers to naturally occurring organic matter that can modify particle stability.

2.4 Effects on treatment performance across wastewater unit processes

The treatment literature shows that interactions between plastics and other particulates can affect biological and physical processes without always causing obvious failure. In sludge systems, the uptake study of Choi and colleagues demonstrated that engineered nanoparticles such as TiO₂ and ZnO attach to primary and secondary sludge particulates, with attachment behavior

depending on mixed liquor suspended solids and ionic strength. The key practical message is that sludge is not merely a passive sink; it is an active collector whose capture efficiency depends on wastewater chemistry. Different degrees of multilayer attachment were observed under different conditions, suggesting that nanoparticle retention is controlled by both surface chemistry and the structure of the sludge matrix. This is especially relevant for plants handling complex influents, because the same conditions that help removal can also drive long term accumulation in biosolids destined for reuse or disposal (Choi *et al.*, 2023).

The impact of nanoplastics on activated sludge is subtler than a simple inhibition story. In the laboratory sequencing batch reactor study by Alvim and colleagues, 100 nanometer polystyrene nanoplastics were fed continuously at low concentration, and organic matter removal was not strongly affected. Even so, the biomass showed signs of response, including changes in microbial composition and moderate heteroaggregation of the nanoplastics. In other words, the treatment process kept working, but the microbial ecology inside the reactor shifted in a way that could matter over longer operating periods or under higher load. This is a useful distinction for wastewater engineering: process stability may look acceptable in short experiments while the biological community is already adapting to an unusual particulate burden. The evidence therefore suggests that performance assessments should examine both effluent quality and biomass characteristics rather than treating them as interchangeable indicators of success (Alvim *et al.*, 2023). Microplastics can also alter sludge architecture and membrane behavior. Jachimowicz and colleagues showed that polyethylene microplastics increased extracellular polymeric substance production in aerobic granular sludge, including alginate, which implies a direct influence on the matrix that governs granule integrity and settling. This matters because extracellular polymeric substances are central to floc formation, granule stability, and resistance to shear. At the same time, the membrane bioreactor study by Wang and colleagues showed that effective membrane interception can trap microplastics over long operating periods, creating accumulation inside the treatment unit. Taken together, these studies reveal a dual effect: plastics may be retained efficiently, but the retained material can still modify sludge properties, promote internal redistribution, or accumulate within process units that were not designed to manage persistent particulate loadings. The result is a treatment system that performs well on paper yet quietly shifts the burden to sludge handling, membrane fouling management, and end disposal pathways (Jachimowicz *et al.*, 2022).

Table 3 summarizes primary findings on particle capture, changes in biological treatment systems, and particle accumulation across major wastewater treatment processes. It justifies Section 2.4, by showing how particle interactions influence treatment performance and sludge behaviour.

Table 3. Primary study evidence on treatment efficiency, process inhibition, and particle redistribution across unit operations

Unit process	Main effect reported	Operational implication	Citation(s)
Sludge handling and nanoparticle capture	ENPs attached to sludge particulates under varying ionic strength and solids content	Sludge becomes a sink and a future release reservoir	(Choi <i>et al.</i> , 2023)

Activated sludge in sequencing batch reactors	Organic removal stayed stable, but biomass and microbial structure changed	Hidden ecological shifts may emerge before visible failure	(Alvim <i>et al.</i> , 2023)
Aerobic granular sludge and membrane bioreactors	EPS increased and plastics accumulated inside the process	Granule structure and membrane operation may be altered	(Jachimowicz <i>et al.</i> , 2022)

ENPs, engineered nanoparticles; TiO₂, titanium dioxide; ZnO, zinc oxide; MPs, microplastics; EPS, extracellular polymeric substances; MBRs, membrane bioreactors.

2.5 Transport pathways and ecotoxicity in receiving environments

Once coupled particle complexes leave treatment plants, their environmental behavior changes again. In the primary sludge fermentation study by Saila and colleagues, polystyrene nanoplastics altered gas production under both acidic and alkaline conditions, and they also promoted the propagation of several antibiotic resistance genes. That is important beyond sludge chemistry because it shows that nanoplastics can affect not only physical transport but also biological and genetic responses in waste streams. The finding supports the idea that particle fate and ecotoxicity are linked: when particles alter fermentation chemistry or microbial gene patterns, the downstream implications extend to sludge reuse, land application, and potential exposure in soil and surface waters (Saila *et al.*, 2024). Receiving waters provide the next stage of that pathway. Zhuang and colleagues showed that ongoing discharge from multiple wastewater treatment plants produced significantly higher microplastic abundance in tributaries than in the main channel of a small watershed, which indicates that local discharge points can dominate spatial patterns in receiving rivers. This is not just a dilution story. Tributaries receiving direct plant effluent can act as particle concentration corridors, especially when multiple treatment plants operate in the same watershed. In parallel, the urban drinking water source study by Zhao and colleagues found higher microplastic abundance in urban areas and downstream of wastewater plants, with smaller 50 to 100 micrometer particles showing stronger correlations with water indicators and microorganisms. Those observations suggest that transported particles may interact with the local microbial community and water quality gradients, making exposure both spatially uneven and biologically relevant (Zhao *et al.*, 2024; Zhuang *et al.*, 2024). The broader ecological implication is that wastewater derived particle complexes are likely to be redistributed across rivers, sediments, and biological interfaces rather than remain confined to the discharge plume. Smaller particles are especially concerning because they can remain suspended longer, travel farther, and interact more strongly with microorganisms and other pollutants. The urban drinking water source study supports that concern by showing that particle properties such as size, color, and shape were more informative than abundance alone when relating plastics to water indicators and microorganisms. That is an important lesson for ecotoxicology. It means exposure assessment should move beyond particle counts and pay attention to which particles are present, where they travel, and what biological interfaces they are likely to meet along the way. For coupled micro and nanoplastic systems, the receiving environment is therefore not a passive endpoint; it is an active arena in which transport, exposure, and toxicity unfold together (Zhao *et al.*, 2024; Zhuang *et al.*, 2024).

Table 4 highlights the major pathways through which particles move from wastewater treatment systems into receiving environments and the biological responses associated with those pathways. It reinforces Section 2.5, by linking particle movement with environmental and

ecological effects.

Table 4. Pathways from wastewater release to receiving environment transport, persistence, and ecotoxicological outcomes

Pathway stage	Main observation	Ecological meaning	Citation(s)
Primary sludge fermentation	PsNPs altered gas production and boosted several resistance genes	Biological responses can begin before environmental release	(Saila <i>et al.</i> , 2024)
Small watershed receiving rivers	Tributaries near WWTP discharges carried more microplastics	Outfalls can shape local transport hotspots	(Zhuang <i>et al.</i> , 2024)
Urban drinking water source	Particle properties correlated more clearly with water quality and microorganisms than abundance alone	Exposure depends on particle identity as well as quantity	(Zhao <i>et al.</i> , 2024)

PsNPs, polystyrene nanoplastics; WWTPs, wastewater treatment plants; ARGs, antibiotic resistance genes; MPs, microplastics.

3. Results and Discussion

3.1 Primary study patterns of co-occurrence in wastewater, sludge, and effluent

Across the primary studies, one message appears again and again: wastewater treatment plants do remove a large share of microplastic particles from the water line, but the removed load does not disappear. It is redirected into sludge, where it becomes concentrated and persistent. In a sludge-based mass balance study, wastewater treatment sludge was shown to function as a major retention compartment for microplastics, confirming that treatment acts more like a transfer mechanism than a true destruction pathway (Alavian Petroody *et al.*, 2021). This pattern matters because once particles are transferred to sludge, they can re enter the environment through land application, leakage during handling, or downstream disposal routes. A field study in Cádiz reached the same general conclusion from a different angle, showing that both industrial and urban plants released MPs into receiving waters while still accumulating large amounts in the wastewater line and sludge fraction (Franco del Pino *et al.*, 2021). More recent multi plant work in Thailand sharpened that picture by showing that centralized plants generally achieved much better removal than decentralized systems, yet both still retained substantial particle loads in sludge. In that study, influent and sludge concentrations were broadly comparable across plant types, but removal efficiencies were far higher in centralized facilities, which suggests that process design and line configuration shape where the particles end up more than whether they are removed at all (Maw *et al.*, 2024). The practical implication is that sludge is not a passive by product; it is the dominant sink where microplastic contamination is stored, concentrated, and potentially redistributed. The literature also suggests that the final profile of the retained material is strongly conditioned by plant architecture. Centralized plants usually combine screening, sedimentation, biological treatment, and sometimes tertiary polishing, so they create more opportunities for particle capture. Decentralized systems often depend on simpler trains and shorter retention times, which reduce the probability that low-density fragments and fibers will be captured before discharge (Maw *et al.*, 2024). In other words, the same waste stream can

behave very differently depending on whether the plant has a full sequence of unit operations or only a compact treatment train. That helps explain why effluent still carries a measurable residual burden even where removal percentages appear impressive on paper. It also helps explain why sludge quality is becoming a growing issue in its own right: the more efficient the water line becomes, the more the pollution burden shifts into solids management (Alavian Petroody *et al.*, 2021; Franco del Pino *et al.*, 2021; Maw *et al.*, 2024).

Figure 1 illustrates the wastewater-treatment train as a redistribution pathway in which microplastics, nanoplastics, and engineered nanoparticles are progressively partitioned between the water and sludge lines, with incomplete capture allowing residual particles to reach final effluent. This directly corroborates Section 3.1 by visualizing the central finding that treatment-associated removal largely transfers particle burdens into sludge rather than eliminating them, while a non-negligible fraction remains in discharged effluent.

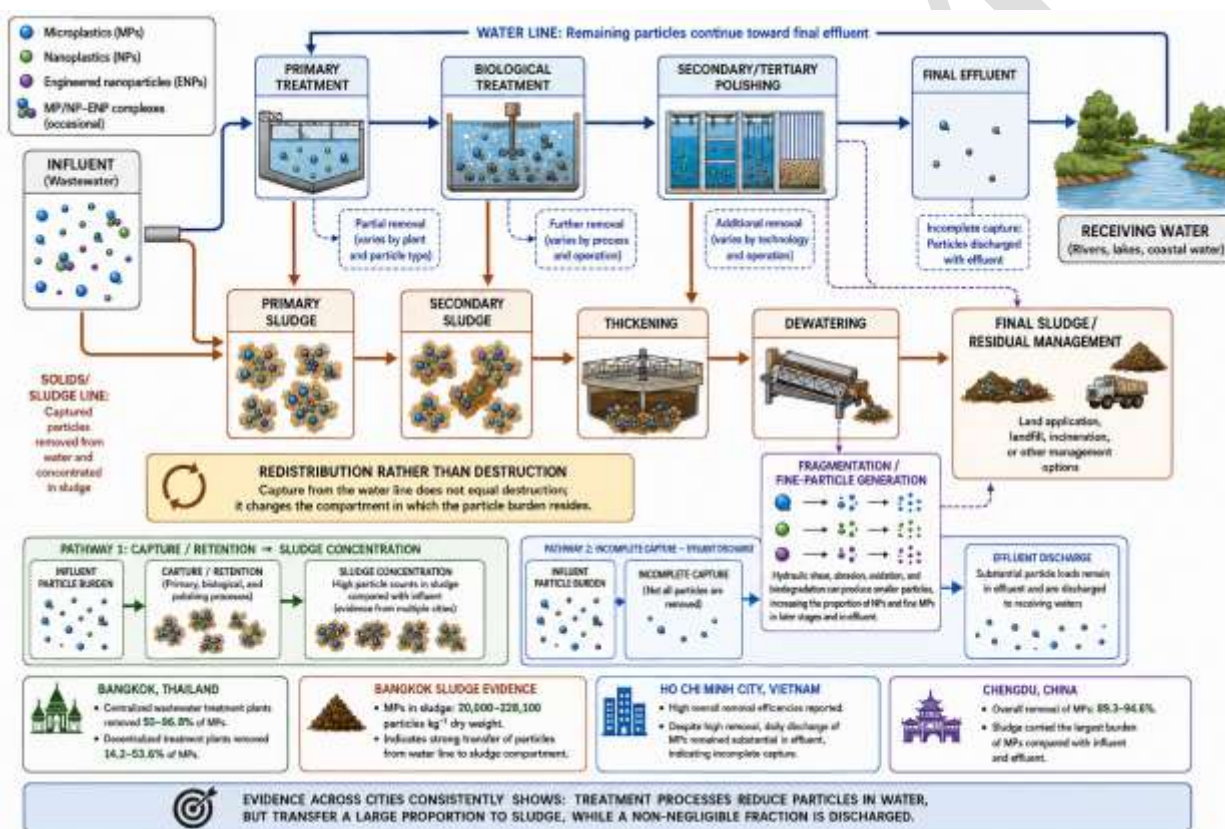


Figure 1. Treatment-Train Redistribution and Partitioning of Microplastics, Nanoplastics, and Engineered Nanoparticles in Wastewater Treatment (Alavian Petroody *et al.*, 2021; Franco del Pino *et al.*, 2021; Maw *et al.*, 2024). Schematic showing the fate of microplastics (MPs), nanoplastics (NPs), and engineered nanoparticles (ENPs) through primary, biological, and secondary/tertiary wastewater treatment, with captured particles transferred to sludge and uncaptured particles discharged in final effluent; occasional MP/NP–ENP complexes represent particle associations. The diagram also depicts sludge thickening, dewatering, fragmentation/fine-particle generation, residual sludge management, and receiving-water discharge, emphasizing redistribution rather than destruction of particle burdens.

Table 5 compares primary studies reporting microplastic occurrence across influent, effluent, and sludge compartments and shows how treatment configuration affects particle retention and discharge. It strengthens Section 3.1, by summarizing differences in particle distribution among treatment systems.

Table 5. Comparative summary of primary studies on influent, effluent, and sludge occurrence.

Study	WWTP context	Main matrix finding	Citation(s)
Transport and accumulation of microplastics through wastewater treatment sludge processes	Sludge line mass balance	Sludge acted as a major sink for retained MPs	(Alavian Petroody <i>et al.</i> , 2021)
Microplastic pollution in wastewater treatment plants in the city of Cádiz	Urban and industrial WWTPs	Effluent still reached receiving waters despite removal	(Franco del Pino <i>et al.</i> , 2021)
Microplastics in wastewater and sludge from centralized and decentralized wastewater treatment plants	Centralized vs decentralized systems	Centralized plants removed MPs more efficiently; sludge loads remained high	(Maw <i>et al.</i> , 2024)

WWTP, wastewater treatment plant; MPs, microplastics; influent refers to wastewater entering the treatment plant; effluent refers to treated wastewater leaving the plant; sludge refers to the solid material retained or produced during treatment.

3.2 Drivers of heteroaggregation, capture, and deposition

The aggregation behavior of micro and nanoplastics is not random. It is shaped by the chemistry of the water, the surface properties of the particles, and the presence of other suspended matter. One of the clearest primary studies on this point showed that nanoplastic aggregation was minimal in pure water and natural river water, but became strong in seawater, where higher ionic strength compressed the electrical double layer and promoted collision driven attachment. The same work also showed that higher temperature and higher particle concentration accelerated aggregation and deposition, which means that marine and warm environments can push nanoplastics out of suspension faster than freshwater systems do (Lee & Fang, 2022). That finding is important because it highlights why transport cannot be discussed without also discussing water chemistry. A particle that remains colloidally stable in a freshwater effluent plume may behave very differently after the same plume reaches a brackish estuary or a marine mixing zone. Figure 2 illustrates the chemistry- and surface-controlled mechanisms governing heteroaggregation, colloidal stability, transport, and deposition of microplastics/nanoplastics in aquatic systems, directly consolidates subsection 3.2 on mechanistic drivers of heteroaggregation and deposition. It emphasizes that ionic strength, pH, salinity, particle surface chemistry, mineral

interactions, dissolved organic matter, temperature, and particle concentration collectively determine whether particles remain dispersed or form aggregates and settle.

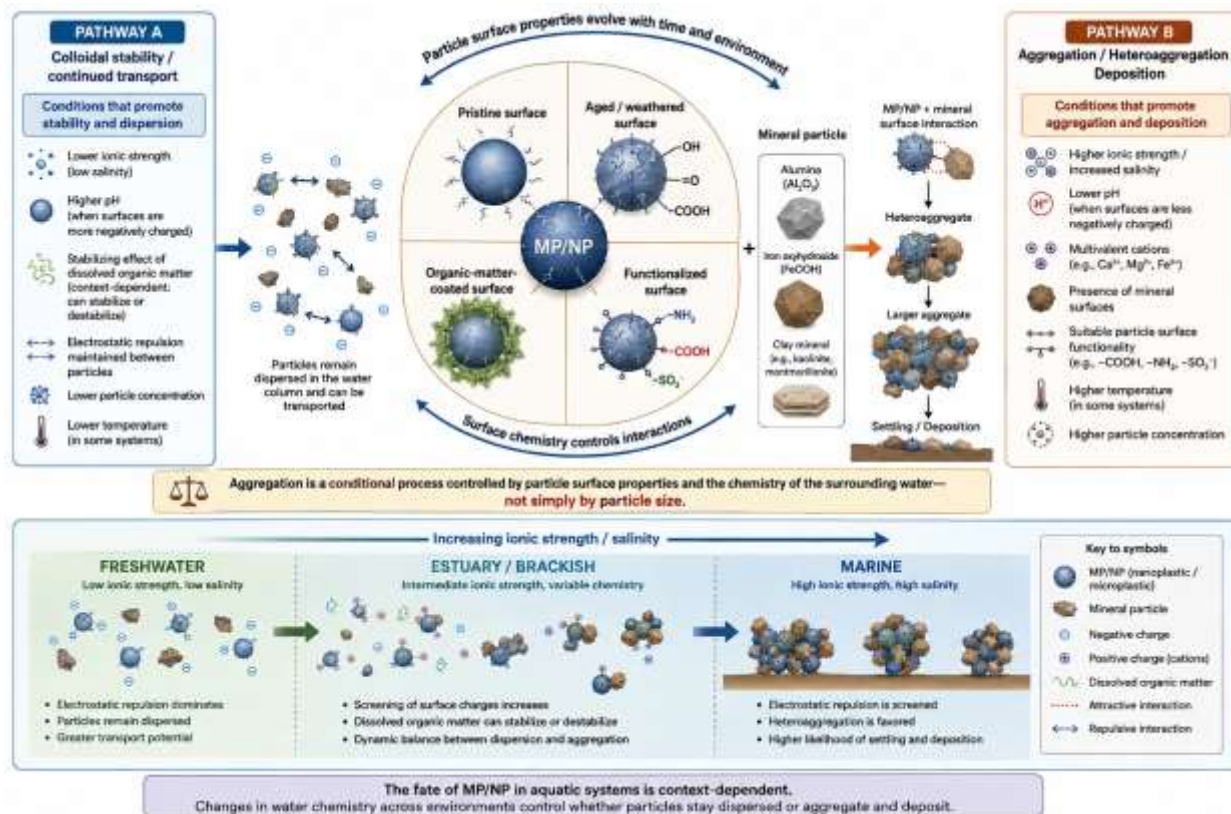


Figure 2. Chemistry- and Surface-Controlled Heteroaggregation, Transport, and Deposition of Microplastics and Nanoplastics (Lee & Fang, 2022; Wang *et al.*, 2023; Wang *et al.*, 2025). Schematic representation of MP/NP surface transformations and their competing environmental fates, showing colloidal stability and continued transport versus mineral-assisted heteroaggregation, aggregate growth, settling, and deposition across freshwater, estuarine/brackish, and marine conditions. Abbreviations: MP/NP, microplastic/nanoplastic; DOM, dissolved organic matter; Al₂O₃, alumina; FeOOH, iron oxyhydroxide; COOH, carboxyl group; NH₂, amino group; SO₃⁻, sulfate group.

Primary work on mineral interactions adds another layer of detail. Experiments with pristine and aged polyethylene microplastics showed that clay minerals can alter settling behavior, but the effect is not driven by clay type alone. Instead, cation valence and plastic aging altered the balance between electrostatic repulsion and aggregation. Aged particles carried more oxygenated functional groups, which improved stability in monovalent electrolyte but not in divalent electrolyte (Wang *et al.*, 2023). This means that environmental aging can either stabilize or destabilize particles depending on the ionic context they enter. A newer mineral particle study extended that logic by demonstrating that heterogeneous aggregation is strengthened by inorganic minerals, protein coating, and higher ionic strength, while increasing pH weakens the interaction (Wang *et al.*, 2025). The combined message is straightforward: heteroaggregation is governed by a three-way interaction among particle surface chemistry, solution chemistry, and

coexisting mineral or biomolecular surfaces.

For treatment and environmental fate, this matter because capture does not depend only on particle size. It also depends on whether the plastic surface is bare, aged, coated with natural organic matter, or bridged by mineral colloids. In practical terms, particles that would otherwise remain suspended may be removed when they encounter mineral fines or multivalent cations, while other combinations remain dispersed and travel farther. The chemistry of the medium therefore acts like a gatekeeper for settling, resuspension, and plume persistence. That is why the best primary studies in this area do not treat aggregation as a simple yes or no event. They treat it as a reversible and context dependent process that can either promote removal or enable longer range transport (Lee & Fang, 2022; Wang *et al.*, 2023; Wang *et al.*, 2025). Table 6 summarizes the major physical and chemical factors tested in primary studies and indicates whether they promote or reduce particle aggregation and deposition. It supports Section 3.2, by showing how environmental conditions influence particle stability and settling.

Table 6. Interaction drivers and the direction of their effects on aggregation and deposition.

Study	Key driver tested	Direction of effect	Citation(s)
Effects of temperature and particle concentration on aggregation of nanoplastics in freshwater and seawater	Ionic strength, temperature, concentration	Seawater and warmer conditions promoted aggregation and deposition	(Lee & Fang, 2022)
Influence of typical clay minerals on aggregation and settling of pristine and aged polyethylene microplastics	Clay minerals, electrolyte valence, aging	Divalent electrolytes destabilized aged particles more strongly	(Wang <i>et al.</i> , 2023)
Heterogeneous aggregation of microplastics and mineral particles in aquatic environments	Surface groups, pH, electrolytes, mineral type	Higher pH reduced aggregation; higher ionic strength enhanced it	(Wang <i>et al.</i> , 2025)

MPs, microplastics; ionic strength describes the concentration of dissolved ions in water; pH, potential of hydrogen; electrolyte refers to a dissolved substance that contributes ions to a solution.

3.3 Consequences for treatment efficiency and sludge management

Primary treatment systems can remove a substantial fraction of plastic particles, but the removal is not equally distributed across plant types or unit operations. In a multi plant study in Guangzhou, influent concentrations were about one order of magnitude higher than effluent concentrations, and total removal efficiencies reached 97.4% to 98.7%. Even so, the retained load accumulated in activated sludge, where concentrations reached 7 to 888 particles per gram dry weight, showing that the treatment train was intercepting particles rather than destroying them (Zhang *et al.*, 2025). A more recent line by line study in municipal plants reinforced the

same pattern. It showed that the water line achieved more than 97% removal overall, but that the sludge line remained the main repository for the recovered particles, with thickening and dehydration stages acting as additional concentration steps (Saur *et al.*, 2025).

Figure 3 illustrates the treatment-efficiency/sludge-management trade-off discussed in subsection 3.3, showing that high microplastic removal in the water line is accompanied by increasing particle retention and concentration in the sludge line. The figure highlights differences among treatment configurations and the potential redistribution of retained particles through land application/reuse, disposal, landfill/leachate pathways, and handling losses.

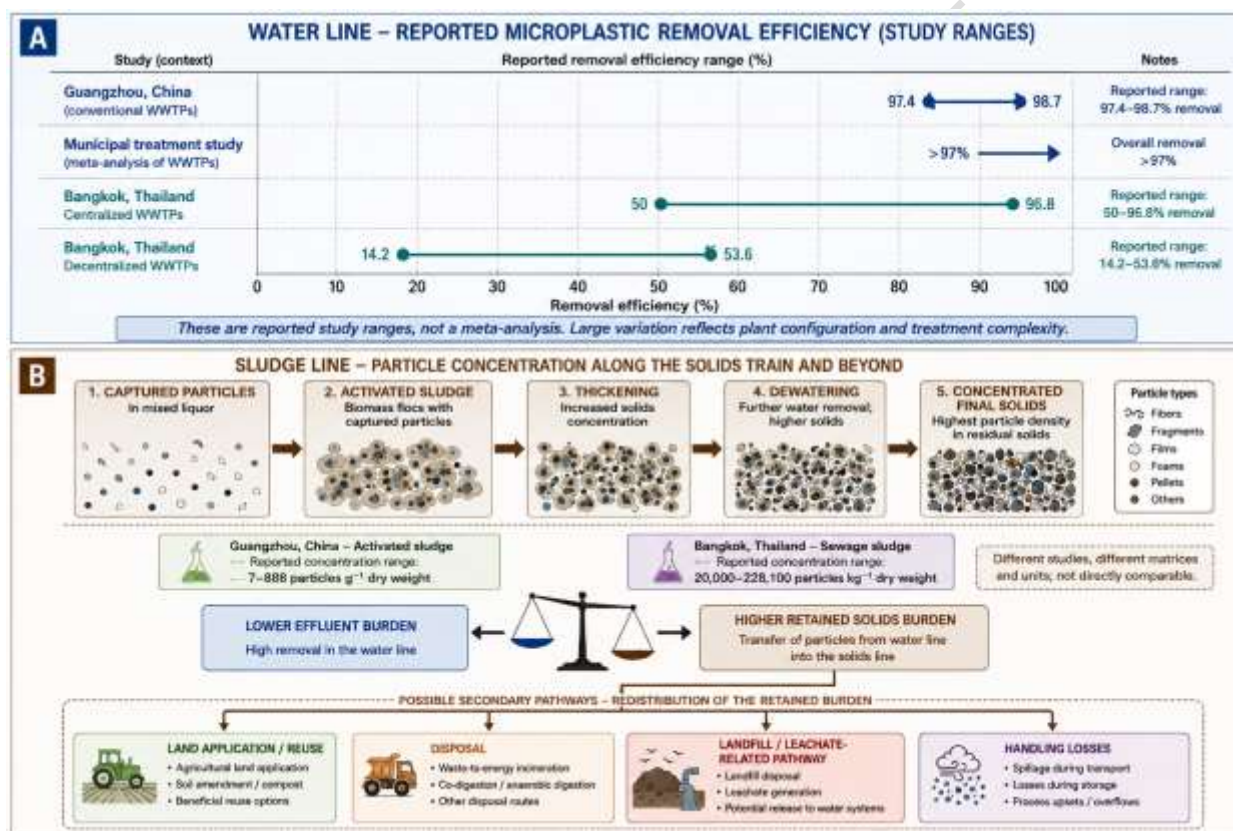


Figure 3. Treatment Efficiency and Sludge-Burden Redistribution of Microplastics in Wastewater Treatment Systems (Maw *et al.*, 2024; Saur *et al.*, 2025; Zhang *et al.*, 2025). Panel A compares reported study-specific microplastic removal ranges for Guangzhou, municipal wastewater treatment, and centralized and decentralized Bangkok plants, emphasizing variation rather than a meta-analysis. Panel B shows progressive particle concentration from captured particles through activated sludge, thickening, dewatering, and final solids, with Guangzhou activated-sludge and Bangkok sludge burdens presented separately; WWTPs, wastewater treatment plants.

The important point is that treatment performance and sludge management are now inseparable. When a plant performs well on the water line, the penalty often appears in the solids line. The centralized versus decentralized study makes this especially clear. Centralized systems in Bangkok achieved removal efficiencies between 50% and 96.8%, while decentralized systems ranged from only 14.2% to 53.6%. Retained MPs in sludge reached 20,000 to 228,100 particles

per kilogram dry weight (Maw *et al.*, 2024). These numbers show that the same pollution stream can be partially intercepted or largely released depending on treatment scale and process complexity. Centralized plants can do a much better job of capture, but that success also means more material enters sludge handling, where it can complicate dewatering, digestion, composting, reuse, and disposal.

There is also a less visible consequence. In several primary studies, the sludge fraction behaved like a conveyor belt for particle redistribution across concentration and dewatering steps (Maw *et al.*, 2024; Saur *et al.*, 2025). That means the final solids are not merely a residue; they are a transformed environmental matrix with a higher particle burden and a different particle profile than the influent. In practical terms, this creates a tradeoff. Better capture in the water line reduces discharge to rivers, yet the burden in sludge can create secondary exposure routes through land application, landfill leachate, or handling losses. The treatment question therefore is not just how many particles are removed, but where they go after removal and whether the sludge line is equipped to contain them safely (Maw *et al.*, 2024; Saur *et al.*, 2025; Zhang *et al.*, 2025). Table 7 presents evidence on the effects of microplastic and nanoplastic interactions on wastewater treatment performance and the corresponding consequences for sludge retention and management. It lends credence to Section 3.3, by illustrating the relationship between particle removal and sludge accumulation.

Table 7. Treatment process implications of micro and nanoplastic-nanoparticle interactions.

Study	Treatment implication	Sludge implication	Citation(s)
Fate of microplastics in urban wastewater treatment plants and their contribution to the receiving river via effluent discharge	High effluent removal but measurable river discharge remained	Activated sludge accumulated a substantial retained load	(Zhang <i>et al.</i> , 2025)
Fate of microplastic pollution along the water and sludge lines in municipal wastewater treatment plants	Water line removed most MPs; sludge line concentrated them	Thickening and dehydration kept concentrating MPs	(Saur <i>et al.</i> , 2025)
Microplastics in wastewater and sludge from centralized and decentralized wastewater treatment plants	Centralized plants outperformed decentralized systems	Sludge retained very high particle loads	(Maw <i>et al.</i> , 2024)

MPs, microplastics; WWTPs, wastewater treatment plants; activated sludge refers to biologically active microbial solids used in wastewater treatment.

3.4 Transport in receiving environments: rivers, lakes, estuaries, and sediments

Once particles leave the plant, their pathway is shaped by the mixing zone they enter. In natural surface water, interactions with engineered nanoparticles can change the way the plastic and the nanoparticle travel together. A primary field experiment showed that when microplastics coexisted with silver nanoparticles in fresh and brackish surface waters, the behavior of the nanoparticles was driven first by water chemistry and only secondarily by the presence of plastic particles. In freshwater, dissolved organic matter kept many AgNPs relatively stable, although some were captured by MPs as single particles. In brackish water, however, higher ionic strength and DOM promoted stronger AgNP aggregation, and some MPs acted as carriers for those aggregates (Li *et al.*, 2022). This matter because it shows that the same particle pair can behave very differently as a plume moves from a river into an estuary. A second primary study helps explain why that shift happens. Nanoplastic aggregation was minimal in freshwater but strong in seawater, and the aggregates became larger and more prone to deposition as temperature and particle concentration rose (Lee & Fang, 2022). That means the receiving environment can actively steer particles toward the sediment compartment rather than leaving them in the water column. In estuaries and coastal zones, this is especially important because the salinity gradient can trigger rapid flocculation and sedimentation, turning a mobile contaminant plume into a benthic exposure source. In practical terms, the sediment compartment should not be viewed as a passive sink; it is often the final exposure hotspot for organisms living at or within the bed. A third study widened the ecological view by showing that MPs and AgNPs together reduced leaf litter decomposition and induced oxidative and neuronal stress across stream fungi and invertebrate detritivores (Trabulo *et al.*, 2024). Although that paper is primarily ecotoxicological, it also carries a transport message: once particles settle into low flow stream habitats, they are no longer just physical contaminants. They become biologically active substrates that can interfere with energy flow, organic matter breakdown, and food web transfer. Taken together, these primary studies show that receiving waters do more than dilute effluent. They transform particle chemistry, alter aggregation and deposition, and define where exposure will occur, whether in the water column, at the sediment surface, or within benthic food webs (Lee & Fang, 2022; Li *et al.*, 2022; Trabulo *et al.*, 2024). Table compares particle transport outcomes across freshwater, brackish water, seawater, and stream environments, with emphasis on aggregation, deposition, and ecological consequences. It supports Section 3.4, Transport in Receiving Environments: Rivers, Lakes, Estuaries, and Sediments, by showing how environmental conditions influence particle movement and accumulation.

Table 8. Transport outcomes across receiving environments.

Study	Receiving environment	Transport outcome	Citation(s)
Insights into the interaction of microplastic with silver nanoparticles in natural surface water	Freshwater and brackish water	DOM and ionic strength controlled AgNP stability and MP capture	(Li <i>et al.</i> , 2022)

Effects of temperature and particle concentration on aggregation of nanoplastics in freshwater and seawater	Freshwater versus seawater	Seawater promoted aggregation and faster deposition	(Lee & Fang, 2022)
Microplastics and silver nanoparticles compromise detrital food chains in streams	Stream habitat	Settled particles affected benthic food web functioning	(Trabulo <i>et al.</i> , 2024)

DOM, dissolved organic matter; AgNPs, silver nanoparticles; MPs, microplastics; freshwater refers to low salinity water; brackish water refers to water with intermediate salinity between freshwater and seawater.

3.5 Ecotoxicity, bioavailability, and research gaps

The ecotoxicology literature is increasingly showing that particle size and co-contaminant context determine how harmful these materials become. In stream food web experiments, MPs and AgNPs reduced growth, suppressed leaf litter decomposition, and induced oxidative stress in fungi and invertebrate detritivores, with mixture effects stronger than single contaminant effects (Trabulo *et al.*, 2024). That is important because it shows that ecological harm can occur even when concentrations are environmentally realistic and even when particles are not directly ingested by vertebrates. The pathway can run through microbial decomposers first, then into detritivores, and then outward through the food web. In other words, the toxicity is not limited to a single organism; it can alter ecosystem function itself. Primary zebrafish studies point in the same direction, but they also reveal a sharper point about nanoplastics. One study found that nanoplastic exposure triggered neurodevelopmental toxicity by activating oxidative stress pathways in zebrafish embryos, indicating that nanoscale particles can reach biologically sensitive targets more easily than larger fragments (Cao *et al.*, 2024). Another study showed that combined exposure to nanoplastics and metal oxide nanoparticles inhibited efflux pumps and caused oxidative stress in embryos, suggesting that the plastic can modify uptake, retention, and cellular stress responses when it travels with engineered nanoparticles (Bhagat *et al.*, 2022). A further zebrafish experiment showed that polystyrene nanoplastics could act as a carrier for silver nanoparticles, alter antioxidant and immune related gene expression, and shift the overall toxicity profile of the metal exposure (Yan *et al.*, 2023). Figure 4 synthesizes the ecotoxicological mechanisms discussed in subsection 3.5, showing how particle size, colloidal mobility, carrier behavior, and combined exposure influence biological uptake, oxidative stress, cellular dysfunction, and organism-level toxicity. It further links these responses across zebrafish embryos and stream fungi/detritivores to sediment exposure and trophic transfer, highlighting the need for size-resolved risk assessment under realistic wastewater-relevant mixtures.

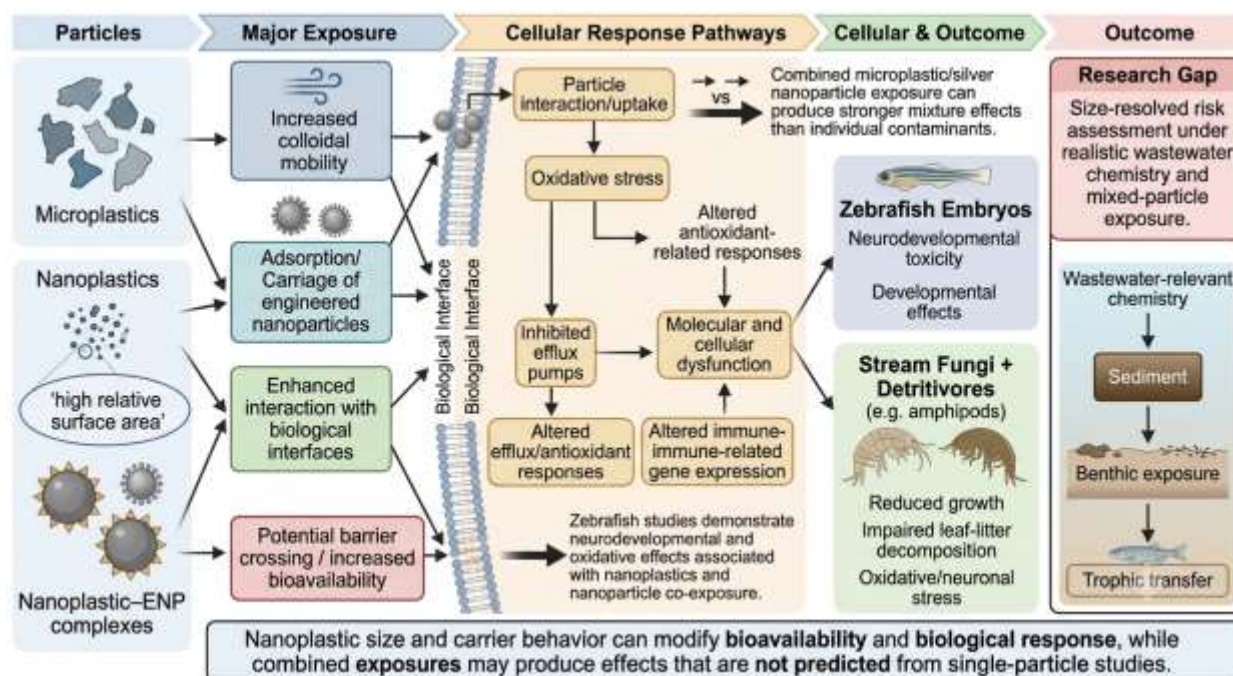


Figure 4. Size- and Mixture-Dependent Ecotoxicity Pathways of Microplastics, Nanoplastics, and Engineered Nanoparticles (Bhagat *et al.*, 2022; Yan *et al.*, 2023; Cao *et al.*, 2024; Trabulo *et al.*, 2024). Conceptual pathway showing how microplastics, nanoplastics, and engineered nanoparticles interact at biological interfaces, undergo uptake and oxidative-stress responses, alter efflux and immune-related pathways, and produce developmental, neurotoxic, ecological, and mixture effects in aquatic organisms. ENP, engineered nanoparticle; AgNPs, silver nanoparticles; “vs.”, versus; e.g., for example.

What emerges from these studies is not simply that nanoplastics are smaller. It is that size changes the route of interaction. Nanoplastics are more likely to cross barriers, adsorb co pollutants, and influence the biological availability of metals and metal oxides. That is why nanoplastics often appear more dangerous than microplastics in toxicity work. Their high surface area, colloidal mobility, and ability to carry adsorbed species make them more chemically and biologically active. The clearest research gap now is size resolved risk assessment under realistic mixtures. Many current studies still focus on one plastic polymer, one engineered nanoparticle, or one model organism at a time. The stronger next step is to test mixed particle systems under wastewater relevant chemistries, then follow them through sediment, benthic exposure, and trophic transfer. Without that shift, risk assessment will continue to underestimate the combined effects that primary studies are already making visible (Bhagat *et al.*, 2022; Yan *et al.*, 2023; Cao *et al.*, 2024; Trabulo *et al.*, 2024). Table 9 summarizes the major biological effects reported in primary studies, including oxidative stress, developmental toxicity, altered growth, and changes associated with nanoparticle exposure. It bolsters Section 3.5, by identifying important findings alongside areas requiring further investigation.

Table 9. Ecotoxicological endpoints reported in primary studies and the associated knowledge gaps.

Study	Ecotoxicological endpoint	Main knowledge gap	Citation(s)
Microplastics and silver nanoparticles compromise detrital food chains in streams	Oxidative stress, reduced decomposition, reduced growth	Need more work on food web scale effects in natural streams	(Trabulo <i>et al.</i> , 2024)
Nanoplastic Exposure Mediates Neurodevelopmental Toxicity by Activating the Oxidative Stress Response in Zebrafish	Neurodevelopmental toxicity and oxidative stress	Need size resolved comparisons across polymers and media	(Cao <i>et al.</i> , 2024)
Combined exposure to nanoplastics and metal oxide nanoparticles inhibits efflux pumps and causes oxidative stress in zebrafish embryos	Transport and oxidative stress responses	Need realistic mixture studies with wastewater chemistry	(Bhagat <i>et al.</i> , 2022)
Polystyrene nanoplastics mediated the toxicity of silver nanoparticles in zebrafish embryos	Carrier mediated AgNP toxicity and immune change	Need bridging studies from embryos to higher trophic levels	(Yan <i>et al.</i> , 2023)

AgNPs, silver nanoparticles; MPs, microplastics; nanoplastics refer to plastic particles within the nanoscale size range; oxidative stress refers to an imbalance between reactive molecules and antioxidant defenses; immune change refers to alterations in immune related biological responses.

Conclusion

This review demonstrates that microplastics, nanoplastics, and engineered nanoparticles are interconnected contaminants whose behaviour in wastewater systems cannot be understood through removal efficiency alone. Wastewater treatment can reduce particle loads in the water line, yet much retained material is transferred to sludge, while fine particles and transformed complexes may remain in effluent and enter receiving waters. Their mobility, aggregation, deposition, persistence, and biological effects are shaped by particle size, surface characteristics, aging, pH, ionic strength, salinity, dissolved organic matter, temperature, and interactions with minerals and other contaminants. The evidence also indicates that mixed exposures alter microbial processes, promote antibiotic resistance patterns, induce oxidative stress, and intensify ecological and developmental effects. Future treatment strategies should adopt a system approach addressing both water and sludge pathways. Attention should focus on particle capture, prevention of fragmentation, and safe sludge management. Routine monitoring should

incorporate size resolved and polymer specific analysis using robust analytical techniques. Research should prioritize realistic mixtures of microplastics, nanoplastics, and engineered nanoparticles under wastewater relevant conditions, including long term and trophic level studies. These approaches will improve environmental risk assessment, guide effective treatment design, and reduce the likelihood that wastewater treatment merely shifts particle pollution from one compartment to another.

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Conflict of Interest Statement

The authors declare that there are no financial, professional, or personal conflicts of interest that could have influenced the preparation, interpretation, or presentation of this comprehensive review. The authors further declare that they have no competing interests concerning the subject matter discussed in the manuscript.

References

- Alavian Petroody, S. S., Hashemi, S. H., & van Gestel, C. A. M. (2021). Transport and accumulation of microplastics through wastewater treatment sludge processes. *Chemosphere*, 278, 130471. <https://doi.org/10.1016/j.chemosphere.2021.130471>
- Alvim, C. B., Ferrer-Polonio, E., Bes-Piá, M. A., Mendoza-Roca, J. A., Fernández-Navarro, J., Alonso-Molina, J. L., & Amorós-Muñoz, I. (2023). Effect of polystyrene nanoplastics on the activated sludge process performance and biomass characteristics: A laboratory study with a sequencing batch reactor. *Journal of Environmental Management*, 329, 117131. <https://doi.org/10.1016/j.jenvman.2022.117131>
- Bhagat, J., Zang, L., Kaneco, S., Nishimura, N., & Shimada, Y. (2022). Combined exposure to nanoplastics and metal oxide nanoparticles inhibits efflux pumps and causes oxidative stress in zebrafish embryos. *Science of the Total Environment*, 835, 155436. <https://doi.org/10.1016/j.scitotenv.2022.155436>
- Cao, X., Xie, W., Feng, M., Chen, J., Zhang, J., Luo, J., & Wang, Y. (2024). Nanoplastic exposure mediates neurodevelopmental toxicity by activating the oxidative stress response in zebrafish (*Danio rerio*). *ACS Omega*, 9(14), 16508–16518. <https://doi.org/10.1021/acsomega.4c00231>
- Carnevale Miino, M., Galafassi, S., Zullo, R., Torretta, V., & Rada, E. C. (2024). Microplastics removal in wastewater treatment plants: A review of the different approaches to limit their release in the environment. *Science of the Total Environment*, 930, 172675. <https://doi.org/10.1016/j.scitotenv.2024.172675>
- Cavazzoli, S., Scopetani, C., Chelazzi, D., Martellini, T., Cincinelli, A., Carretti, E., Ascolese, M., Gori, R., Mair, K., Tirler, W., Donegà, M., & Andreottola, G. (2026). Effectiveness of conventional municipal wastewater treatment plants in microplastics removal: Insights from multiple analytical techniques. *Journal of Environmental Sciences*, 160, 424–438. <https://doi.org/10.1016/j.jes.2025.04.035>
- Cervantes-Avilés, P., & Keller, A. A. (2021). Incidence of metal-based nanoparticles in the conventional wastewater treatment process. *Water Research*, 189, 116603. <https://doi.org/10.1016/j.watres.2020.116603>
- Choi, S., Johnston, M., Wang, G.-S., & Huang, C.-P. (2023). The uptake of engineered nanoparticles by sludge particulates. *Water*, 15(16), 2872. <https://doi.org/10.3390/w15162872>
- Dong, S., Cai, W., Xia, J., Sheng, L., Wang, W., & Liu, H. (2021). Aggregation kinetics of fragmental PET nanoplastics in aqueous environment: Complex roles of electrolytes, pH and humic acid. *Environmental Pollution*, 268, 115828. <https://doi.org/10.1016/j.envpol.2020.115828>
- Franco del Pino, A. A., Arellano, J. M., Albendín, G., Rodríguez-Barroso, M. R., Quiroga, J. M., & Coello, M. D. (2021). Microplastic pollution in wastewater treatment plants in the city of Cádiz: Abundance, removal efficiency and presence in receiving water body. *Science of the Total Environment*, 776, 145795. <https://doi.org/10.1016/j.scitotenv.2021.145795>
- Guo, Y., Tang, N., Lu, L., Li, N., Hu, T., Guo, J., Zhang, J., Zeng, Z., & Liang, J. (2024). Aggregation behavior of polystyrene nanoplastics: Role of surface functional groups and protein and electrolyte variation. *Chemosphere*, 350, 140998. <https://doi.org/10.1016/j.chemosphere.2023.140998>
- Iskandarani, S., Manjunath, S., Busquets, R., Raeli, L., Saikaly, P. E., & Campos, L. C. (2025). Characterization of nanoplastics and small-sized microplastics in sewage treatment.

- Scientific Reports*, 15, 30089. <https://doi.org/10.1038/s41598-025-15504-9>
- Jachimowicz, P., Jo, Y.-J., & Cydzik-Kwiatkowska, A. (2022). Polyethylene microplastics increase extracellular polymeric substances production in aerobic granular sludge. *Science of the Total Environment*, 851, 158208. <https://doi.org/10.1016/j.scitotenv.2022.158208>
- Kieu-Le, T.-C., Ngo, T.-P., Lai, M.-T., Pham, N.-H., Nguyen, N.-B.-T., Nguyen, P.-D., Le, T.-M.-T., & Strady, E. (2025). Microplastics in wastewater and sludge from centralized industrial wastewater treatment plants in Ho Chi Minh City, Vietnam. *Case Studies in Chemical and Environmental Engineering*, 12, 101276. <https://doi.org/10.1016/j.csee.2025.101276>
- Lee, C. H., & Fang, J. K. H. (2022). Effects of temperature and particle concentration on aggregation of nanoplastics in freshwater and seawater. *Science of the Total Environment*, 817, 152562. <https://doi.org/10.1016/j.scitotenv.2021.152562>
- Li, P., Liu, J., & Zhang, H. (2022). Insights into the interaction of microplastic with silver nanoparticles in natural surface water. *Science of the Total Environment*, 805, 150315. <https://doi.org/10.1016/j.scitotenv.2021.150315>
- Lv, J., Huang, T., Wu, B., Hu, X., Ding, Y., & Zhang, Y. (2025). Distribution characteristics of microplastics in wastewater treatment plants in mega cities: The case study of Chengdu City. *Scientific Reports*, 15, 31405. <https://doi.org/10.1038/s41598-025-17146-3>
- Maw, M. M., Boontanon, N., Aung, H. K. Z. Z., Jindal, R., Fujii, S., Visvanathan, C., & Boontanon, S. K. (2024). Microplastics in wastewater and sludge from centralized and decentralized wastewater treatment plants: Effects of treatment systems and microplastic characteristics. *Chemosphere*, 361, 142536. <https://doi.org/10.1016/j.chemosphere.2024.142536>
- Miserli, K., & Konstantinou, I. (2025). Determination of microplastics in municipal wastewater treatment plant effluents and sludge using micro-Raman spectroscopy. *Water Emerging Contaminants & Nanoplastics*, 4(1), 4. <https://doi.org/10.20517/we.cn.2024.72>
- Monira, S., Roychand, R., Hai, F. I., Bhuiyan, M., Dhar, B. R., & Pramanik, B. K. (2023). Nano and microplastics occurrence in wastewater treatment plants: A comprehensive understanding of microplastics fragmentation and their removal. *Chemosphere*, 334, 139011. <https://doi.org/10.1016/j.chemosphere.2023.139011>
- Moon, S., Martin, L. M. A., Kim, S., Zhang, Q., Zhang, R., Xu, W., & Luo, T. (2024). Direct observation and identification of nanoplastics in ocean water. *Science Advances*, 10(4), eadh1675. <https://doi.org/10.1126/sciadv.adh1675>
- Okoffo, E. D., & Thomas, K. V. (2024). Quantitative analysis of nanoplastics in environmental and potable waters by pyrolysis-gas chromatography-mass spectrometry. *Journal of Hazardous Materials*, 464, 133013. <https://doi.org/10.1016/j.jhazmat.2023.133013>
- Ren, H., Zhao, H., Wang, H., Niu, B., Wang, Y., Lu, Y., Jiang, G., Zhang, Z., & Hao, Z. (2025). Identification and assessment of microplastics in wastewater treatment plants using laser direct infrared spectroscopy and depolymerization-coupled liquid chromatography-tandem mass spectrometry. *Journal of Hazardous Materials*, 495, 138852. <https://doi.org/10.1016/j.jhazmat.2025.138852>
- Saila, R., Zakaria, B. S., Mirsoleimani Azizi, S. M., Mostafa, A., & Dhar, B. R. (2024). Impact of polystyrene nanoplastics on primary sludge fermentation under acidic and alkaline conditions: Significance of antibiotic resistance genes. *Chemosphere*, 364, 142777. <https://doi.org/10.1016/j.chemosphere.2024.142777>

- Saur, T., Paillet, F., Robert, S., Alibar, J. C., Loret, J. F., & Barillon, B. (2025). Fate of microplastic pollution along the water and sludge lines in municipal wastewater treatment plants. *Microplastics*, 4(2), 19. <https://doi.org/10.3390/microplastics4020019>
- Trabulo, J., Pradhan, A., Pascoal, C., & Cássio, F. (2024). Microplastics and silver nanoparticles compromise detrital food chains in streams through effects on microbial decomposers and invertebrate detritivores. *Chemosphere*, 367, 143656. <https://doi.org/10.1016/j.chemosphere.2024.143656>
- Tran, T. T., Stenger, K. S., Strømmen, M., Bezuidenhout, C. C., & Wikmark, O.-G. (2025). Microplastic categories distinctively impact wastewater bacterial taxonomic composition and antimicrobial resistance genes. *Microorganisms*, 13(2), 260. <https://doi.org/10.3390/microorganisms13020260>
- Vardar, S., Onay, T. T., Demirel, B., & Kideys, A. E. (2021). Evaluation of microplastics removal efficiency at a wastewater treatment plant discharging to the Sea of Marmara. *Environmental Pollution*, 289, 117862. <https://doi.org/10.1016/j.envpol.2021.117862>
- Wang, J., Zhao, X., Wu, A., Tang, Z., Niu, L., Wu, F., Wang, F., Zhao, T., & Fu, Z. (2021). Aggregation and stability of sulfate-modified polystyrene nanoplastics in synthetic and natural waters. *Environmental Pollution*, 268, 114240. <https://doi.org/10.1016/j.envpol.2020.114240>
- Wang, Y., Chen, X., Wang, F., & Cheng, N. (2023). Influence of typical clay minerals on aggregation and settling of pristine and aged polyethylene microplastics. *Environmental Pollution*, 316, 120649. <https://doi.org/10.1016/j.envpol.2022.120649>
- Wang, Y., Tang, Z., Liu, Y., Qian, Y., Yang, S., Wang, A., Dong, Z., & Xing, B. (2025). Heterogeneous aggregation of microplastics and mineral particles in aquatic environments: Effects of surface functional groups, pH, and electrolytes. *Environmental Chemistry and Ecotoxicology*, 7, 848–858. <https://doi.org/10.1016/j.eneco.2025.04.012>
- Wu, J., Liu, J., Wu, P., Sun, L., Chen, M., Shang, Z., Ye, Q., & Zhu, N. (2022). The heteroaggregation and deposition behavior of nanoplastics on Al₂O₃ in aquatic environments. *Journal of Hazardous Materials*, 435, 128964. <https://doi.org/10.1016/j.jhazmat.2022.128964>
- Xu, Y., Wang, X., van der Hoek, J. P., Liu, G., & Lompe, K. M. (2025). Natural organic matter stabilizes pristine nanoplastics but destabilizes photochemical weathered nanoplastics in monovalent electrolyte solutions. *Environmental Science & Technology*, 59(3), 1822–1834. <https://doi.org/10.1021/acs.est.4c11540>
- Yan, Z., Zhou, Y., Zhu, P., Bao, X., & Su, P. (2023). Polystyrene nanoplastics mediated the toxicity of silver nanoparticles in zebrafish embryos. *Frontiers in Marine Science*, 10, 1195125. <https://doi.org/10.3389/fmars.2023.1195125>
- Zhang, Q., Zhou, S., Li, Z., Zhang, Y., Ouyang, W., & Mai, L. (2025). Fate of microplastics in urban wastewater treatment plants and their contribution to the receiving river via effluent discharge. *Journal of Oceanology and Limnology*, 43, 372–382. <https://doi.org/10.1007/s00343-024-4138-1>
- Zhao, W., Jiang, J., Liu, M., Tu, T., Wang, L., & Zhang, S. (2024). Exploring correlations between microplastics, microorganisms, and water quality in an urban drinking water source. *Ecotoxicology and Environmental Safety*, 275, 116249. <https://doi.org/10.1016/j.ecoenv.2024.116249>
- Zhuang, L., Zhang, Y., Xue, Y., Yanfang, R., Ren, Y., He, J., & Sun, H. (2024). Influence of ongoing discharge from multiple wastewater treatment plants on microplastic patterns in

small-scale receiving rivers. *Science of the Total Environment*, 932, 172880.
<https://doi.org/10.1016/j.scitotenv.2024.172880>

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